X-923-76-74

NASA TM X- 71119

EXCERPTS FROM SELECTED LANDSAT 1 FINAL REPORTS IN GEOLOGY

NICHOLAS M. SHORT
A. SMITH
R. BAKER

(NASA-TM-X-71119) EXCERPTS FROM SELECTED LANDSAT 1 FINAL REPORTS IN GEOLOGY (NASA) 79 p HC $5.00 CSCL 08G

N76-32621

Unclas
G3/43 04097

APRIL 1976

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-923-76-74

EXCERPTS FROM SELECTED LANDSAT 1 FINAL REPORTS IN GEOLOGY

Nicholas M. Short
NASA, Goddard Space Flight Center
Greenbelt, Maryland 20771

A. Smith
R. Baker
General Electric Space Division
Glendale, Maryland 20771

April 1976

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

AN EVALUATION OF LANDSAT 1 FINAL REPORTS IN GEOLOGY

INTRODUCTION

Sixty-seven of the 315 NASA-approved investigations in the Landsat 1* program were classed into the Geology (Mineral Resources, Geologic Structure, and Landform Analysis) Discipline. As of March 1, 1976, forty-six Type III Final Reports summarizing the results of these investigations in Geology had been received by the Mission Utilization Office at Goddard Space Flight Center; of these 15 were in draft form and the remainder have now been accepted as complete.

These final reports are submitted to three reviewer groups for scientific evaluation: (1) N. M. Short, Earth Resources Discipline Leader in Geology; (2) H. A. Tiedemann, Landsat Discipline Leader in Geology, and (3) A. Smith and R. Baker, support personnel for Geology from the General Electric Co. Space Division. Information is extracted systematically by these individuals and then summarized in various formats for inhouse and public release uses. The standard format is a condensed synopsis of selected information entered into a computer-based Significant Results File. Useful information is also frequently singled out for incorporation into NASA program reviews, Symposium workshop proceedings, professional journal and magazine articles, and presentations at meetings and lectures.

On the whole, the investigation final reports have proved to be informative, comprehensive, and in some instances definitive. However, the reports vary considerably in content, coverage, style, effective documentation, analysis and appraisal of results, and recommendations for follow-on work. In addition, many basic questions of interest to professional geologists, programs managers, and technical support personnel in evaluating the Landsat system for geologic applications are being raised by individuals without access to the reports. Answers to these are often difficult to recognize and collate even in the several formats summarizing the information extracted from the reports and other sources.

In an effort to identify and evaluate the contents of the final reports relevant to these basic questions, the senior author of this Document prepared his own checklist of basic categories of information to be sought in the Type III Final Reports. These categories are listed in Table 1. Most of the category topics are self-explanatory; others are clarified by the investigator quotations entered in the category sections elsewhere in this Document.

* Previously known as ERTS-1 (Earth Resources Technology Satellite)

Table 1

Evaluation of Landsat 1 Final Reports

Check List for Geology

1. Value of Landsat Data to Geology Discussed	16	19. Aircraft Remote Sensor Data Utilized	1
2. Geologic Benefits Listed	12	20. Aerial Photos Used and Compared	9
3. Limitations of Landsat for Geological Applications Considered	10	21. Skylab Data Used & Compared	4
4. Improvements (in future) satellites) Proposed	3	22. Radar Data Used & Compared	3
5. Follow–Up Studies Proposed	8	23. Relative Percent of Same Features noted in Landsat, EREP, A/C	2
6. Cost Benefits Stated	7	24. Field Checks Carried Out and Role of Field Work Considered	11
7. Optimum Working Scales Evaluated	4	25. Geophysical Data Correlated with Landsat Data	7
8. Tests of Reliability (Quantification) Utilized	1	26. Rock Types Discriminated and/or Identified	8
9. Statistical Analyses Conducted	5	27. Rock Unit Contacts Selected	12
10. Natural Enhancement Effects (Snow, etc.) Noted	11	28. Comparisons Made with Published Geologic Maps	12
11. Optical Enhancements Used	8	29. Relative Mapping Accuracies in Humid, Semiarid, Arid Settings	0
12. Computer Enhancements or Analyses Performed	9	30. Geomorphic Units Recognized and Characterized	10
13. Multispectral Classification (e.g., Clustering) Attempted	2	31. Comparisons to Known Linear Features Made	10
14. Seasonal Coverage Advantages Examined	11	32. Types, Sizes, Distributions, and Orientations of Linears Noted	11
15. Temporal Changes Observed (Relative to Dynamic Events)	2	33. Relative Linears Count between Summer & Winter Images	0
16. Relations to Soil and/or Vegetation Considered	6	34. Linears Related to Tectonics	7
17. Specific Small Features Looked for (Resolution Test)	3	35. Alternation Zones Detected	2
18. Stereo Effects Utilized	6	36. Exploration Model(s) Developed	6

In order to determine how effectively the final reports address the basic questions (categories) and to record a representative selection of specific answers, a total of 18 Type III Final Reports were carefully reviewed using the checklist as a means for picking out responses to the questions implicit in the categories. For example, the question may be posed: "What are the particular benefits to Geology obtained from Landsat data analysis?" Answers to this, perhaps presented informally in several places within a report or stated emphatically in a section under a particular heading, would be gathered into category 2, Geologic Benefits Listed, in the checklist. Or again, the question "Is it possible to recognize individual formations or other stratigraphic units or subdivisions in Landsat imagery?" would prompt answers collected into category 27, Rock Unit Contacts Selected.

The choice of which 18 final reports to be evaluated from the 31 in hand by March of 1976 was made somewhat arbitrarily. The 18 Principal Investigators and the title of each report are given in Table 2. Most were picked because of their evident thoroughness of documentation and/or their recognized impact on the geologic community as demonstrated through presentations of related material by the investigators at professional meetings. No slight or criticism of the remaining 13 investigators (or those whose reports are still in draft stage) omitted from this evaluation is intended in any way.

After selection of the 18 reports for evaluation, the actual information extraction was carried out by A. Smith and R. Baker of the General Electric Co. Space Division. This involved a detailed reading of the report to find specific responses to the questions defined by the categories. The responses are structured in this Document as direct quotations from the reports rather than paraphrases of the information identified. Some quotations are slightly condensed and a few have been edited as needed.

Table 1 also records the number (sum) of reports which provided a quotable response or entry for each category. No attempt is made to relate any individual report to the number given in the table. However, the reader can determine precisely those investigators who offered some answer(s) by searching through the following main section of this Document.

This section consists of one or more pages devoted to each of the categories for which responses were given. The respondee is identified at the beginning of each quotation used by a pair of letters in parentheses representing two key letters in the last name of the Principal Investigator. The letter code for each investigator is shown in Table 2.

Table 2

Principal Investigator	Title of Final Report
(AG) Abdel-Gawad, M.	Identification and Interpretation of Tectonic Features from ERTS-1 Imagery
(Br) Brockman, C. E.	Earth Resources Technology Satellite Data Collection Project-ERTS-1, Bolivia
(Co) Collins, R. J.	An Evaluation of ERTS Data for the Purposes of Petroleum Exploration
(Ge) Gedney, L. D.	Evaluation of Feasibility of Mapping Seismically Active Faults in Alaska
(Ho) Houston, R. S.	Analysis of ERTS-1 Imagery and Its Application to Evaluation of Wyoming's Natural Resources
(Is) Isachsen, Y. W.	Assessment of ERTS-1 Imagery As a Tool for Regional Geological Analysis in New York State
(Kn) Knepper, D. H.	Geologic and Mineral and Water Resources Investigations in Western Colorado Using ERTS-1 Data
(Ko) Kottlowski, F. E.	Geologic Analysis of ERTS-1 Imagery for the State of New Mexico
(Kr) Krinsley, D. B.	The Utilization of ERTS-1 Generated Images in the Evaluation of Some Iranian Playas as Sites for Economic and Engineering Development
(La) Lathram, E. H.	Identification of Geostructures of the Continental Crust Particularly as They Relate to Mineral Resource Evaluation
(Li) Liggett, M. A.	A Reconnaissance Space Sensing Investigation of Crustal Structure for a Strip from the Eastern Sierra Nevada to the Colorado Plateau
(Mc) McKee, E. D.	A Synthesis of Sand Seas Throughout the World

Table 2 (Continued)

Principal Investigator	Title of Final Report
(Mo) Mohr, P. A.	Mapping of the Major Structures of the African Rift System
(Mr) Morrison, R. B.	Evaluation of ERTS-1 Imagery for Mapping Quaternary Deposits and Landforms in the Great Plains and Midwest
(Ro) Rowan, L. C.	Iron-Absorption Band Analysis for the Discrimination of Iron-Rich Zones
(Sa) Saunders, D. F.	ERTS-1 Imagery Use in Reconnaissance Prospecting
(Sc) Schmidt, R. G.	The Use of ERTS-1 Images in the Search for Large Sulfide Deposits in the Chagai District, Pakistan
(Vi) Vincent, R. K.	Surface Compositional Mapping by Spectral Ratioing of ERTS-1 MSS Data in the Wind River Basin and Range, Wyoming

1. Value of Landsat Data to Geology Discussed

(AG) Using Landsat imagery to study major faults in Northern Mexico and across the border into the U.S., we arrived at the conclusion that the entire southwestern part of North America was subject to large-scale left-lateral regmatic shear.

Study of regional metamorphic grain of the Precambrian basement complex across the Red Sea shows that the Arabian-Nubian Masif can be divided into three main parts.

(Br) The major application of the Landsat images is directed to structural geology. The images show faults which are impossible to identify through conventional methods.

Landsat imagery can be used to construct regional geological maps and also to correct, complete and check existing maps.

(Co) Perhaps the most important aspect of Landsat is that it provides the exploration geologist a new perspective for looking at the earth and reveals new avenues of inquiry.

Landsat data is useful for inferring lithologic distribution.

Lithologic contacts seen on Landsat imagery are so distinct and clear we believe that they can be used to revise published information.

Value and advantages of Landsat for lithologic mapping.

- Large areas can be mapped quickly.
- Major structural and lithologic features are discernable.
- Existing interpretations of some local areas can be improved.
- Regional relationships among lithologic, structural and geomorphic features can be studied.
- Areas for further study or geophysical work can be located.
- Some units can be subdivided on the basis of their reflectivities.
- Interpretation permits evaluation and revision of published information.
- Low resolution and regional coverage suppress or eliminate a large amount of distracting detail permitting subtle scale differences to be defined and studied.

(Co) Landsat is also an excellent map for planning logistics, overflights, the location of operations bases, etc.

(Ge) Mosaics were found to be of the greatest value in defining regional structural relationships, and in pointing out large features which would have been otherwise overlooked.

It appears that most earthquakes in Alaska can be associated with lineaments which are visible on the imagery. The potential significance of this in terms of future construction planning, zoning, and seismic risk evaluation is obvious.

(Ho) Successful applications demonstrated by investigators include: (1) general geologic mapping; (2) structural and tectonic studies; (3) land form and surface processes; (4) mineral explorations; (5) land-use inventories, . . .

The Landsat synoptic view is unparalleled . . . for regional studies . . . and for preparing reconnaissance geologic maps by establishing key lithologic units . . .

A previously unstudied area has been mapped using Landsat. The large area involved, rugged topography, lack of control and general inaccessibility had discouraged a regional investigation.

(Is) The synoptic value of ERTS-1 imagery is readily appreciated from a single satellite image, but perhaps even more from a mosaic of an entire state where, despite the loss in resolution due to 2.5x photo reduction of the original mosaic, major physiographic, geologic, and tectonic provinces can be seen.

The most significant contribution of ERTS-1 imagery . . . in New York State has been the location of more than 400 . . . linears in the Adirondacks which had not previously been recognized.

ERTS-1 side-illuminated imagery, combined with known ground conditions, well displays the amazingly detailed control of topography by structure. The imagery permits mapping of most of the major faults and topographic lineaments previously known, as well as the boundaries of physiographic, geologic, and tectonic provinces. The greatest contribution of new data in New York State is in the field of regional tectonic analyses, more especially in the delineation of new linear features, many of which have been verified on the ground, and circular features which remain problematical.

(Kn) "Many specific geologic phenomena can be discerned on Landsat-1 imagery, and almost all . . . can be viewed in a geologic context"

- Basic geologic information - rocks and soils, geologic structures, landforms.

"The amount of geologically relevant information that can be interpreted from Landsat-1 imagery far exceeds expectations."

(Ko) Perhaps the most important feature of Landsat imagery is its small scale and synoptic view which allows the identification of regional trends.

Landsat imagery is a valuable tool in obtaining additional information on geologic structure, geomorphology, hydrology, and land use in an arid environment.

(Kr) Landsat-1 generated images constitute an important tool for evaluation of some Iranian Playas as sites for economic and engineering development. Even when used alone and interpreted far from the image area, an experienced earth scientist can make many sound inferences concerning the hydrology, morphology, and to some extent the gross pedology of the playas.

(La) Results demonstrate conclusively the practical application of Landsat data to the study of geology of Alaska, and to the analysis of its mineral resource potential.

Landsat images are being used to complete a revised 1:1,000,000 scale regional map of northern Alaska. Aerial photographs were found to provide little additional data, whereas Landsat images revealed a pronounced and possibly important structural pattern.

Landsat images are being used operationally to evaluate the mineral resource potential of selected Alaska quadrangles.

(Li) The synoptic scale of the ERTS-1 MSS imagery has permitted the recognition of large geologic features, trends and patterns often obscured by detail at the scale of low altitude aerial photography or conventional geologic mapping. These anomalies are expressed in ERTS-1 imagery by such characteristics as surface coloring and texture, topography and vegetation patterns. Using ERTS-1 MSS imagery, the Cenozoic tectonic framework of the test site has been studied at a scale and level of detail not possible using available tectonic map compilations. This study has

(Li) documented an interrelationship between the Cenozoic tectonics of the southern Basin and Range Province and the regional distribution of seismic activity, volcanism, plutonism and related mineralization and geothermal activity. This research has resulted in new concepts of Basin and Range tectonics and related structural control of igneous activity and mineralization.

ERTS-1 MSS imagery can be a valuable tool for reconnaissance exploration of mineral, geothermal and ground water resources, and for regional study of geologic hazards. Used as part of an integrated exploration or research program, anomalies selected from ERTS-1 data can be economically narrowed and evaluated using a variety of geophysical, geochemical and geologic techniques.

The ERTS-1 MSS imagery has proven to have an effective balance of scale, resolution and spectral range for applications to reconnaissance geologic investigation. The primary advantage of the ERTS-1 MSS imagery is the synoptic perspective of terrane, which permits the study of regional distributions or patterns of spectral and spatial features related to geologic and structural phenomena.

The spectral range and the multispectral format of the ERTS-1 MSS data have proven suitable for a variety of image enhancement and analysis techniques. The control of color balance and contrast range possible in false-color compositing of the ERTS-1 MSS imagery is greater than that feasible in the processing of conventional color photography.

The primary advantage of the ERTS-1 imagery is the ability to conduct reconnaissance hydrologic studies of large areas more economically than with conventional techniques. Use of the ERTS-1 data in a reconnaissance program provides information on basin geometry, vegetation, drainage patterns, soil and rock types, and structural control of ground water distribution. These data can be used to guide investigators to areas of high potential in which more expensive ground based geologic and geophysical techniques can be concentrated for maximum efficiency.

(Mc) Analysis of Landsat imagery has resulted in an objective classification of sand-sea landforms that is believed to have worldwide application.

Surface relief in the Namib sand sea had not been reliably mapped until Landsat-1 imagery provided a data base. Available O.N.C. and U.S. Coast & Geodetic Survey maps show large areas.

(Mc) Through the study and analysis of Landsat images, the basic patterns of sand-sea accumulations throughout the world have, for the first time, been directly compared under conditions of a uniform, constant scale. The obvious advantages of these comparisons are that basic types of sand bodies can be recognized, their global distribution determined, and their relationship to other physical features such as mountains, water bodies, and wind directions ascertained.

(Mo) The virtue of Landsat is that it provides in map form the regional tectonic pattern of earth's crust . . .

The prime value of Landsat imagery to structural geology is the regional scale on which structural features can be sought, identified, and mapped.

The overall structural pattern of the African Rift System is seen in its unity for the first time.

Accurate, small scale lithological mapping is possible for some areas.

Landsat imagery enormously facilitates regional structural mapping.

(Mr) ERTS images are important new tools for rapid small scale mapping of surficial geologic materials and geomorphic features; and for investigating megascale geologic-geomorphic anomalies.

This project demonstrated the possibility of rapid systematic mapping and analysis of gross landform/surficial geologic units . . .

The images facilitate distinguishing and mapping soil associations for both agronomic and engineering applications.

Better quality ERTS images allow the subdivision and mapping of relatively small geologic terrain units, generally more accurately than by the use of topographic maps alone.

Perhaps the most important aspect of the analyses made possible by the ERTS synoptic overview is that they point out places where field investigations might be most profitable.

(Ro) Landsat images provide a means for more completely evaluating regional tectonic and structural patterns, especially as they apply to potential mineral deposits.

(Ro) For landform and many other geological studies, the most critical aspect of the MSS images is the synoptic and essentially planimetric view at nearly constant illumination.

(Sa) Landsat imagery is of great value in photogeologic interactions of regional features, and that the model developed provides a means of relating data from Landsat to structures that have controlled emplacement of ore deposits and hydrocarbon accumulations . . .

. . . it is concluded that the mapping and application of Landsat data at 1:1,000,000 scale will provide a workable and economically advantageous new reconnaissance prospecting approach for gold, base metals, uranium, and fluid fossil fuels.

It is concluded that Landsat lineament interpretation provides continental-scale structional information that photos cannot.

2. Geologic Benefits Listed

(AG) A fault lineament was identified . . . which shows evidence of recent faulting associated with moderate seismic activity.

. . . the ability to identify areas . . . where specific faulting is indicated can be of considerable value . . . for the evaluation of earthquake hazards.

A most important result . . . which has direct practical applications is the ability to recognize and map fault lines showing evidence of Holocene breakage.

Geologic and structural analysis . . . resulted in the selection of 17 target areas for mineral exploration; of which three areas were found to show evidence of mining . . . not known before . . .

(Br) Landsat data has been used, in lieu of adequate maps, as a basis on which to plan future oil leases and determine geologic structures.

Landsat has provided new information on the relationship and regional distribution of volcanic centers . . .

For the first time, a great deal of detail about the hydrographic network has been acquired.

Landsat data are being used to prospect for new mineral resources, in civil works, and in groundwater exploration.

The data obtained from the interpretation of the Landsat images combined with drilling data has resulted in the identification of a potential petroleum area.

Landsat data are being used to produce the first volcanological map of Bolivia.

By combining lineament maps with existing maps of mineralized zones, it is possible to determine the parameters which control mineral deposition.

(Co) Landsat data are extremely useful during the initial phases of petroleum exploration. Our work convinces us that by studying Landsat data one can gain an understanding of regional lithologic and structural relationships.

(Ge) The satellite imagery is far exceeding our expectations in fault scarp resolution under favorable lighting conditions.

(Ho) Fossil playa lakes could be mapped using Landsat if exposed in a sedimentary succession.

Red-bed facies of the Tertiary of Wyoming can be identified on Landsat because of their distinctive yellowish hue on color composites . . .

Use of Landsat with other data has demonstrated a practical application . . . in prospecting for groundwater.

Landsat proved successful in distinguishing terrane of mafic metamorphic rocks (greenstone) from that comprising mostly felsic rocks (granite-gneiss).

Landsat's regional view . . . made it possible to map glacial features, landforms, dune fields, playa deposits, and regional facies.

Landsat imagery has also proven useful for topical studies such as mapping of flood plains (with distinction between natural vegetation and irrigated flood plain), regional vegetation maps, rangeland mapping, mapping of major soil types, slope estimation, mapping of strip mining operations, mapping of potential areas of mineral development, . . .

Sand dune maps prepared from Landsat imagery are being used by archeologists in Wyoming as a source of information about dunal trends and possible archeological site locations.

(Kn) (Lithologic discrimination) . . . different rock and soil types commonly result in different surface expressions, and these differences can be <u>interpreted</u>, although specific units cannot be identified.

Among the most easily detected contacts in the study scenes were: bedrock vs. alluvium; sedimentary vs. crystalline; sedimentary sequences (folded or tilted).

Six mappable units can be discriminated in the Uncompahgre/Paradox area, largely due to the lack of soil cover and sparse vegetation.

(Ko) Lineaments and curvilinear features have been identified which may lead to the discovery of new mineral deposits.

(Li) The synoptic scale of the ERTS-1 MSS imagery has permitted the recognition of large geologic features, trends and patterns often obscured by detail at the scale of low altitude aerial photography or conventional geologic mapping. These anomalies are expressed in ERTS-1 imagery by such characteristics as surface coloring and texture, topography and vegetation patterns. Ground based reconnaissance of anomalies recognized in ERTS-1 imagery has resulted in identification of previously unreported strike-slip and normal fault systems, structural ground water traps, dike swarms, domal plutonic structures, volcanic centers, and areas of hydrothermal alteration.

(Mc) Where sand movement affects projects of human development as through burial or by altering the surface water regime, drought conditions commonly develop. Such conditions are present today in the Rajasthan Desert of India and near Lake Chad and elsewhere along the margins of the Sahara Desert. Thus, the basic facts concerned with the growth and development of sand-seas as developed by Landsat imagery, supplemented by Skylab photography and by ground truth furnished through trenching, are essential to a successful management program in these drought areas.

(Mo) Landsat imagery has facilitated a major advance in accurate mapping and better understanding of the African rift valleys.

Landsat facilitates the mapping of volcanic centers, related flows, and faults.

Considerable detail could be extracted from the Landsat imagery concerning the fold structures and major lithological elements of the Yemeni basement.

Landsat imagery reveals the regional extent of the Tana Graben for the first time.

3. Limitations of Landsat for Geological Applications Considered

(Br) Folds were very difficult to identify on Landsat images.

(Co) Difficulties and limitations of Landsat for lithologic mapping.

- Many mapped rock units have similar reflectivities and cannot be distinguished from each other on Landsat.
- Large areas are covered by Recent to Quaternary deposits. The total area is somewhat greater than previously mapped. These deposits mask older units.
- Small scale and low resolution limit precision of locating boundaries and identifying small or isolated lithologic features.
- Landsat rock units usually do not coincide exactly with published units. Even the multispectral nature of Landsat data does not permit identification of lithology or rock composition. These parameters can only be inferred crudely from geomorphology, drainage texture, relief, etc.

Because of the small scale and low resolution Landsat interpretation can contribute relatively little during the detailed phases of exploration.

(Ge) One disappointing aspect of Landsat imagery has been that the stereo effect obtained by viewing side-lapping pairs in a stereoscope is negligible.

(Ho) Some areas are not suitable for geological mapping because dips are steeper, structure more complicated, and vegetation tends to mask rock types.

The main limitations of the Landsat data are low resolution and lack of stereoscopic coverage.

The mapping of altered sandstone was only partly successful using Landsat imagery . . . the identification of black sandstone deposits was unsuccessful because of resolution.

(Ko) Landsat imagery is a complement to and not a substitute for aerial photography.

Vegetation cover is a major obstacle to geologic rock unit mapping in New Mexico.

(Ko) Many normal faults are covered by alluvium and are not visible.

(La) It is evident that determination of the . . . significance of a space image linear cannot rely solely on examination of exposed geologic conditions . . .; study of subsurface geologic data . . . is necessary.

(Li) A primary limitation of the ERTS-1 imagery has been in studying at a local scale, geologic and structural features such as folds, foliation and irregular lithologic contacts. Although large exposures of surface material can often be distinguished by color, texture or erosional morphology, specific rock or soil types cannot generally be identified by composition. Surface coloring and small structural features are easily masked by vegetation.

Due to generally low dips and irregular traces, thrust faults are the most difficult of these structures to recognize except where distinctive rock types have been juxtaposed.

It is unlikely that ERTS-1 MSS data could be used effectively in a hazards study without the support of detailed geologic and structural information.

(Mo) Landsat imagery cannot distinguish among different types of faults or, except for major transcurrent faults, the amount of displacement among them . . .

By lacking the capability for stereoscopic emphasis, it (Landsat) cannot be used to identify regional vertical upwarps.

(Mr) Limited topographic information was available due to the limited capability for stereoscopic viewing.

Relatively little new basic information was generated by the mapping, because of the moderate resolution of the ERTS images and because in most of the areas studied present knowledge has advanced beyond the capability of interpretation from ERTS imagery.

(Ro) It is noteworthy, however, that only 15 percent of all the mapped faults were . . . identified as linears.

Compilation of <u>all</u> linear features . . . evident in Landsat without regard for scale results in a large data set which is composed of features having different origins, . . . different degrees of geologic validity, etc. . .

Geologic and geophysical analysis of these features <u>individually</u> is impractical, and statistical analysis of the entire set appears to be unsound . . .

4. Improvements (in future satellites) Proposed

(Ge) The stereo effect would probably be enhanced considerably if the spacecraft were equipped with obliquely mounted cameras.

(Vi) The success of the R 5/4 ratio in detecting iron compounds is dependent on strong absorption in the green by the presence of the Fe^{3+} ion with concomitant high reflectivity in red. This spectral information is not necessarily adequately exploited by the wide bands of Landsat. Narrowing of those bands, with selective optimal placement for Fe^{3+} absorption feature, should result in increased sensitivity and improve levels of detectability.

5. Follow Up Studies Proposed

(Ko) Several follow-up studies have been proposed, including:

1. Drainage corrections on New Mexico maps from the Landsat Mosaic of New Mexico should be made.
2. Lineament mapping should be extended to other areas in the state and lineament orientations defined. This would include a regional tectonic analysis of the western part of New Mexico.
3. Isolineament mapping and its relation to mineral deposits should be investigated.
4. Vegetation patterns as surrogates for mineral zones and geothermal areas should be studied.
5. Environmental impact as related to vegetation should be studied.

(La) . . . Concerted effort should be made by geologists versed in the regional geology of large areas of North America, individually or as teams, to analyze the giant linears and circular features visible on Landsat, to determine their significance . . .

(Li) Although the effectiveness of ERTS-1 data may vary with geologic and climatic settings, we are confident that the analysis and interpretation procedures developed in this investigation will help extend the use of ERTS-1 data to other parts of the world, where regional structural reconnaissance and related applications to resource exploration have not been economically feasible in the past.

(Mc) The classification system of sand-seas based on areas studied should be tested against sand-seas in other parts of the world.

An atlas should be published showing the range of desert landform types discernible on Landsat imagery.

(Mr) Additional ERTS-1 type imagery is justified for detecting time variant phenomena such as zones of inundation by large floods, areas burned by prairie fires, changes in land use, phenological changes in agricultural and natural lands and vegetational and geologic changes wrought by droughts.

(Ro) To select the best wavelength bands for future spectral experiments, digital image techniques, and models, In situ spectral reflectivity measurements coordinated with analyses of representative areas should be acquired.

Digital computer and color compositing techniques should be calibrated and standardized as much as possible . . .

The effects of spatial resolution, stereographic coverage and of temporally influenced factors should be fully investigated.

6. Cost Benefits Stated

(AG) The utilization of Landsat imagery to identify and map potentially active faults can significantly reduce the cost and effort of planning detailed field investigations . . . Landsat imagery can conceivably reduce the total areas to be examined . . . and the cost by a factor of 100 . . .

(Co) When assuming several constant factors and other significant data in a cost benefit statement on the use of Landsat for exploration, a Landsat-oriented exploration project would represent approximately a 30% savings over a conventional exploration program.

(Ho) Accurate cost/benefit analyses cannot be made for most applications . . . some rough cost estimate can be made . . . by estimating the improvement in mapping efficiency . . . In terms of time saved in compiling the 1:250,000-scale land-use map, a 4-fold reduction in interpretation was estimated . . .

For regional geologic mapping, . . . using Landsat as a mapping base could result in a 3-fold savings . . .

(Kn) "Analysis of photolineament information contained on Landsat imagery can be a very valuable and inexpensive first step in any mineral exploration program."

"Plotting frequency of linear intersections, combined with the location of "reddish-brown" color anomalies, appears to be a relatively quick and effective way of isolating primary target areas for metallic mineral exploration."

(Li) Within the geologic and climatic terrane of the test site, the use of ERTS-1 MSS imagery in natural resource exploration and management is estimated to permit cost savings of approximately 10 to 1 over conventional reconnaissance techniques.

At an optimum level of study, geologic analysis of ERTS-1 imagery is estimated to cost approximately $10,000 per scene covering roughly 13,200 square miles (33,800 square km), or less than $1.00 per square mile. Such a study would include image enhancement and analysis processing, research and analysis of subsidiary geologic, geophysical, and remote sensing data, ground based reconnaissance of key areas, and related overhead expenses. An investigation of this nature would be expected to result in selection of key exploration anomalies representing less than 5 percent of the original 13,200 square mile area. The selection of comparable exploration areas, using other reconnaissance techniques, is considerably more expensive. Reconnaissance geologic mapping, comparable in resolution to the ERTS-1 imagery,

(Li) would probably need to be at the scale of 1:100,000 or 1:200,000. The costs for such reconnaissance mapping in the southwestern United States are estimated at between $60 and $200 per square mile. The range in costs for acquisition of several alternate types of remote sensing data over the western United States is estimated below. These estimates are based on experience and on data cited by Carter and others (1972).

Black and white aerial photography - $3.00 to $10.00/square mile

Color or multispectral aerial photography - $10.00 to $40.00/square mile

Thermal-infrared imagery - $5.00 to $30.00/square mile

Low resolution aerial magnetometry - $10.00 to $50.00/square mile

Multiple airborne geophysics - $50.00 to $150.00/square mile

Although the use of ERTS-1 imagery would typically be confined to the reconnaissance phases of an exploration program, its application can result in significant cost savings. Comparisons with other techniques suggest cost savings in excess of 10 to 1 for reconnaissance exploration in the semiarid terrane of the southwestern United States.

The information gained from analysis of ERTS-1 MSS imagery is complementary to data from ground based geohydrologic studies. Based on our work in the southern Basin Range Province, hydrologic reconnaissance using ERTS-1 imagery, including limited ground based study, is estimated to cost approximately $8,000 per scene (13,200 square miles or 33,800 square km). The cost of ground based hydrologic mapping of comparable scale is estimated to be approximately $100 per square mile, excluding detailed geochemical or geophysical surveys. The potential cost savings gained by using ERTS-1 imagery in reconnaissance hydrologic exploration in the arid southwestern United States are estimated to be approximately 10 to 1 over conventional reconnaissance techniques.

Analysis and interpretation of ERTS-1 data for application to reconnaissance geothermal exploration is estimated to cost less than $1.00 per square mile.

In comparison with the use of ERTS-1 MSS imagery, other reconnaissance techniques applicable to geothermal exploration are considerably more expensive. The costs of geologic mapping at a scale of 1:100,000 or 1:200,000 are estimated to be between $60 and $200 per square mile; aeromagnetic surveys from $10 to $50 per square mile; reconnaissance gravity surveys from $150 to $300 per square mile; and thermal infrared imaging from $5 to $30 per square mile.

(Li) The use of ERTS-1 imagery for reconnaissance of potential geothermal sources can significantly reduce the overall size of the area that would need to be surveyed using the more expensive geologic and geophysical techniques cited above. In reconnaissance exploration, the application of ERTS-1 data is believed to provide potential cost savings on the order of 10 to 1.

Reconnaissance study of geologic and structural hazards using ERTS-1 data is estimated to cost approximately $10,000 per scene (13,200 square miles) or less than $100 per square mile (2.5 square km). Such an investigation would include imagery enhancement processing, field reconnaissance and literature and map research resulting in selection of key anomalies for more detailed investigation. Reconnaissance mapping of geologic hazards at a scale of approximately 1:200,000 using conventional mapping techniques is estimated to cost between $25 and $100 per square mile in terrane typical of the western United States. Low altitude color or multispectral aerial photography can cost an additional $40 per square mile.

Based on these cost comparisons, the application of ERTS-1 data to reconnaissance study of geologic hazards in the southwestern United States is estimated to permit savings on the order of 10 to 1 over conventional reconnaissance techniques.

(Mc) Examples of preliminary analyses of sand-seas given in this report show that the cost of analyses of various remote deserts by interpretation of satellite imagery is only a fraction of the cost of surveying even one desert by means of airplane, jeep, or camel. Because of the very difficult conditions for carrying out aerial and ground surveys, no reliable and comparable data base for many of these regions was available before Landsat-1 began to acquire imagery. The vast sand-seas of the world are probably the last remaining land areas of which the surfaces have not been reliably mapped by civilian agencies, so information supplied by Landsat is a unique contribution of knowledge of these areas.

(Sa) Analysis has shown that the use of Landsat imagery as a product for regional scale structural studies is about 1/500th as expensive as using conventional aerial photography.

. . . the cost ratio for interpretation is concluded to be about 10:1; that is, a linear interpretation task requiring 10 days if using aerial photomosaics could be accomplished in one day if Landsat were used.

Editor's Note: None of the above cost estimates is balanced against the relative loss of quality and quantity of some information in Landsat data as compared to most conventional methods (e. g., mapping from aerial photos or on the ground).

7. Optimum Working Scales Evaluated

(Co) Prints at a scale of 1:250,000 were better than 1:1,000,000 for most geologic analyses.

Transparencies are easier to work with and interpret and also provide some additional visual detail.

. . . we feel that one scale has no real interpretative advantages over the other.

Bands 5 and 7 are most useful for initial geologic interpretation; contain largely redundant information.

. . . color composites contain the most information . . . and makes interpretation easier and quicker.

(Is) Various geologic features, including subdivisions within the Appalachian fold belt, the Hudson Highlands and the belt of Taconic allocthons can be seen better at the 1:500,000 scale (as opposed to the 1:1,000,000).

A major problem associated with field checking of ERTS-1 anomalies is locating them on the ground. As indicated earlier, this is greatly facilitated by visually transferring data from the ERTS-1 photographic product to another photographic product at a more useful field scale, namely airfoto index sheets at 1:62,500. It is then relatively easy to transfer the feature to the approximately correct location on 1:62,500 topographic maps, particularly if it is a topographic one.

For southeastern New York, more linears, both topographic and tonal, were observed at the 1:1,000,000 scale than at any other scale. Several consistent variations can be seen in going from smaller to larger scales.

- Continuous topographic linears become zones of discontinuous aligned segments, and the same applied to tonal linears.
- Many topographic linears become tonal linears.

(Li) Based on comparison of the ERTS-1 data analysis with other hydrologic studies in the test site, it is estimated that the satellite data is suitable to guide reconnaissance geohydrologic studies at scales of 1:125,000 and possibly larger.

(Li) In geologic and climatic terrane such as that found in the southwestern United States, ERTS-1 data can be readily applied to the reconnaissance of potentially active fault systems, landslide areas and areas prone to flash-flooding and extensive erosion by wind or water. The synoptic scale and resolution of the ERTS-1 data is estimated to be sufficient to guide investigations at map scales of approximately 1:200,000 or possibly larger.

8. Tests of Reliability (Quantification) Utilized

(Ro) The high reliability (approximately 80 percent) of identification of altered areas indicates a large potential for this technique in mineral exploration.

9. Statistical Analyses Conducted

(Is) A comparison of rose diagrams for summed lengths of linears of the Catskill Mountains and summed number of joints in the study area is shown in Figures 66a and 66b. The diagram of linears shows an arc of strong maxima between N 15 E and N 35 E, whereas that for joints shows two prominent directions, one generally east-west and the other between N 5 W and N 15 E. This discrepancy may well be due to the fact that we are comparing a complete sample of linears with only a small, road-controlled sample of the joints in the region. The east-west joints may correspond to the very short east-west linear sets which pervade the Catskills but add relatively little magnitude to the summed-length diagrams.

(Kn) After all the detectability evaluations were completed for the 24 lithologic contacts, statistical tests were run on various subsets of the data matrix. These tests compare the mean detectability of a data subset with the mean detectability of another subset, producing information as to whether the means are statistically different at a given level of significance (a value). Three types of tests were used (3):

1. Standard F-test at a = 0.05
2. Confidence intervals at a = 0.05
3. Duncan multiple-range test at a = 0.05

The standard F-test and the Duncan multiple-range test are relatively rigorous statistical tests. Confidence intervals are useful in visualizing the variability between a large number of populations.

Six different subsets of the data matrix were analyzed:

1. Overall band - to compare the relative usefulness of the 4 Landsat-1 bands
2. Overall image set - to determine if the time of year the imagery was acquired affects the detectability of contracts, regardless of band
3. Overall contact - to determine if some contacts are easier to detect than others, regardless of band and time of year
4. Contact/band - to determine if specific contacts are best detected on any particular band

(Kn) 5. Contact/image set - to determine if specific contacts are best detected on any particular image set (time of year)

6. Band/image set - to determine if any particular band is best for a given image set (time of year)

During the statistical testing of the detectability data, it was discovered that:

1. There is no "best" band within any of the image sets studied.
2. There is no "best" band for any of the contacts studied.
3. Overall, band 5 is best.

Another set of statistical tests showed that:

1. The detectability of individual lithologic contacts is sensitive to image set (time of year) and the best detectabilities occur on different image sets for different contacts.
2. Overall, image set does not affect the detectability of the lithologic contacts in general.

(La) A quantitative analysis of the linears was made . . . The shorter linears show a more random distribution than the regional ones, but a gross similar orientation pattern is suggested.

(Mr) Figure 21 shows a series of rose diagrams to display statistically the coincidence of linear valley orientations with known structural orientations. The present valleys show a wider scatter of data around the preferred orientations than do the buried bedrock valleys. This may be caused by the complicating influence of Pleistocene surficial deposition.

The multiplicity and regional pattern of these linears also suggests that the majority of them are related to fractures of little or no displacement.

(Ro) An azimuth-frequency analysis has been carried out by computer for the major lineaments . . . Results show that the most common azimuth is due north . . . The least frequently occurring azimuth is around N 60°W.

10. Natural Enhancement Effects (Snow, etc.) Noted

(Kn) Seasonal, daily, and hourly factors may act to enhance or subdue the surface and image expression of all three terrain components:

1. Shadowing at low sun-elevation angles enhances topography; high sun-elevation subdues topographic expression.
2. Snow cover subdues or hides the actual spectral contrast between adjacent lithologic units; shadows produced by low sun-elevation angles may produce the same effect.
3. Vegetation contrast may be either enhanced or subdued due to snow cover, and vegetation contrasts vary with phenology.

Maximum topographic enhancement occurs when sun-angles are the lowest possible. This occurs in mid-winter in Colorado, a time when snow cover is commonly complete.

Maximum spectral contrast occurs when the sun is high (contact not shadowed) and the contact is free of snow and vegetation (contact is exposed).

Maximum vegetation contrast occurs at different times of year depending on (1) the specific types of vegetation involved, and (2) its geographic location.

(Ko) It was found that band 7 was more suitable for structure in areas of dense vegetation and high relief. In arid basins and in areas of low relief where shrubs and grass predominate, band 5 was equally as good as band 7 and even preferable in some cases.

Late fall and early winter imagery was used to take advantage of low sun angle and the consequent enhancement of geologic structure.

(Li) Natural enhancement/color anomalies associated with mineral deposits are due to alteration or mineralization of a variety of host rocks. Color anomalies are easily masked by vegetation cover.

Topographic expressions of known altered or mineralized areas are visible in ERTS imagery and include:

- margins of plutons - arcuate topographic depressions;
- volcanic centers - basaltic flows and cones, circular features; and

- faults - primary surface breaks, structurally controlled in-place weathering and erosion.

(Mr) Landforms and landform associations are interpreted primarily from agricultural patterns, including not only field patterns, but also the patterns of pasturelands, woodlands, and rural roads.

Certain landforms and geologic features also can be interpreted indirectly from analysis of stream density, stream dissection and drainage patterns, and stream-divide relations — again mainly as revealed by land use patterns.

A continuous snow cover masks out distracting information from vegetation and soils, but, because of the shadowing resulting from the low sun-elevation angle of the winter images, details of topography are much enhanced.

Subtle tonal variations indicate the types of glacial and other surficial deposits and landforms upon which soils have developed. Dark tones indicate poor drainage.

(Ro) The sun azimuth angle at the time the Landsat images were acquired may be in part responsible for the relatively low percentage of faults missed in the northeasterly and east-northeasterly direction.

(Sc) An excellent impression of relative topographic relief can be obtained from the Landsat images . . . The relative topographic relief combined with the photogeologic maps is a powerful interpretative tool.

11. Optical Enhancements Used

(Br) Color composite images were found the most valuable for soils mapping.

(Co) Electronic edge enhancement and density slicing helped little.

Photographic techniques are cheap, simple, and can be quite useful. Techniques used included high contrast printing, gray scale adjustment, and film sandwiches.

Color additive viewing is flexible and is useful for enhancing specific features such as linears, closed anomalies, and lithologic boundaries.

Several types of enhancement (photographic, additive color viewing, etc.) should be tried in any operational program once areas of interest are defined.

(Ho) General mapping capability was increased by use of . . . color-additive viewing, isodensity slicing, snow scenes, edge enhancements, . . .

(Kn) "None of the various photo optical image enhancement techniques used will produce an image that is in all respects superior to single band, black and white Landsat-1 images. The various enhancement techniques used cause enhancement of one or more geology-related surface phenomena at the expense of serious image degradation resulting in images that are less useful than standard, single-band black and white Landsat-1 images for general geologic interpretation.

The techniques examined included:

Color additive viewing - especially useful for identifying red rocks.

Composites from Color Separates - useful for simulating color IR images.

Density Slicing and contrast enhancement.

Color compensating filters. Several steps in the gray scale of a Landsat image can be isolated and color coded using this method. The Landsat scene used in this study was initially a fairly low-contrast scene of the San Juan Mountains in southwestern Colorado. The pseudo-color separation produced greatly increased the contrast of the original image and some of the topographic and geomorphic features were greatly enhanced, especially drainage textures and

(Kn) the annular drainages of the Silverton, Lake City and Creede Calderas. This method may definitely be an aid to an interpreter by bringing out the more obscure details present in originally low-contract Landsat scenes.

(Ko) An I^2S Digicol Viewer and an Addcol Viewer were found to be less useful than false-color composites provided by NASA.

A Xerox copy made of one image was found to enhance the linear structures of that scene.

The Digicol Viewer was used to attempt to enhance linear features; results were not significant.

(Kr) A three-stage masking technique was employed in the construction of a false-color diazo composite map of the hydrologic changes. A black-and-white negative was prepared from the Landsat-1 MSS, 9.5 inch positive transparency of band 7. The negative of band 7 then was combined with the positive transparency of band 4 from that same scene to form a sandwich; and, a positive transparency was made from this sandwich. A false-color diazo was made from each of these positive transparencies. These false-color diazos were combined and superposed on a simple false-color diazo composite made from positive transparencies of band 5 and band 7.

False-color composites of Qom Playa containing bands 4, 5, and 7 (yellow, red, and blue, respectively) approach reality with respect to earth materials and water, and permit a generalized surficial geologic and hydrologic analysis. False-color-ratio composites in certain combinations both accentuate and delineate subtle differences in spectral reflectivity that are easily ignored or are not visible in the simple false-color composites of Qom Playa. Contrast between areas and within zones is much sharper and color differences highlight these distinctions.

(Li) The authors describe and evaluate the following image enhancement techniques:

- Edge enhancement
- Additive color viewing
- High resolution false color compositing
- Dye transfer color compositing
- Spectral ratioing

(Li) - Moire' pattern analysis

- Optical Fourier Transform Analysis
- Pseudo relief enhancement

(Mc) To date the best method for rapid quantitative analysis is density slicing.

12. Computer Enhancements or Analyses Performed

(Co) Digital processes offer the greatest range of possibilities but must be "fine tuned" for each area. Unless a completely interactive system is available this can be a long process. Techniques that seem to be the most useful are density slicing, gray scale adjustment and ratio operations.

(Ho) . . . the LARS programs, . . . and GE's IMAGE 100, . . . have been employed in this study. . . A major effort has been to establish a capability for . . . Landsat computer processing, . . . including: (1) minicomputers, (2) sequential Q-mode factor pattern recognition, . . .

One . . . major difficulty in using digital computers . . . is the necessity of utilizing alphanumeric map plots . . .

(Is) No new linears were found in the scene nor were previously observed linears notably enhanced. This is probably because the density level spread on the original imagery of bands 5 and 7 was already favorable for linear detection.

After experimentation with a number of photographic, optical and digital enhancement techniques, we conclude that, for the humid northeast, linear and circular features are most advantageously "mapped" using false color composite transparencies of the best fall imagery, supplemented by the best winter imagery. Almost fully as satisfactory, however, is the utilization of infrared imagery (band 7) for fall and winter. Limited experimentation with the NASA/GSFC program for image processing (IDAMS) suggest that some additional detail may be recovered on the shaded sides of mountains using the program sequence for contrast stretching, color compositing, and enlarging.

(Kr) Because of their generally uniform appearance, playa surficial materials are usually sampled randomly, in the absence of any conspicuous differences in textures, moisture, relief, or color. The use of a computer-enhanced image permits the earth scientist to concentrate on specific areas of discrete image color changes which must reflect differences in hydrology, composition, and relief, or some subtle combination of all three.

(Li) Several image enhancement techniques were developed for effective analysis of the ERTS-1 data. High resolution false-color compositing of multispectral imagery, with precise control of image color balance and contrast range, has been a primary tool. Edge enhancement printing has proven useful for studying structural trends expressed by patterns of topography and drainage. False-color spectral ratio imaging has been effective for enhancing subtle reflectance differences between rock and soil types, and in studying the distribution and density of vegetation.

Additive color viewing has been effective in determining the optimum MSS band-filter combinations for enhancing spectral information. High resolution color enlargements have been employed in detailed laboratory and field analysis. Band ratioing techniques have been used for differentiating rock and vegetation anomalies in ERTS-1 imagery over a large area around Las Vegas, Nevada.

(Ro) A technique which combines digital computer processing and color compositing has been devised for detecting hydrothermally altered areas.

In situ spectral reflectivity measurements coordinated with mineralogical and chemical analyses of . . . selected samples are the soundest basis for refining image processing techniques.

(Vi) Surface minerals with relatively high reflectance in the red region and low in the green can be mapped using the MSS 5/4 ratio in arid and semi-arid terrains where vegetation cover is not extensive. Hematite, geothite and limonite . . . are good examples of such surface minerals.

Corrected ratio images were made independent of environmental changes (atmosphere and solar zenith angle) to within a standard error ($\leq$10%).

It was found that a temporal ratio map of an R 7/5 spectral ratio uncorrected by dark object subtraction and ratio normalization was more independent of atmospheric and solar illumination than a single channel radiance maps . . . Moreover, a corrected temporal ratio map was found to be more independent of atmospheric and solar illumination than either of the above maps.

Vincent indicates that "this preliminary exercise in automatic recognition using multiple ratio inputs was successful for some specific targets, but not all."

13. Multispectral Classification (e.g., Clustering) Attempted

(Kn) "The detectability of lithologic contacts and geologic structures on Landsat imagery is relatively insensitive to spectral band.

14. Seasonal Coverage Advantages Examined

(Co) Bands 5 and 7 acquired during periods of maximum or minimum vegetation vigor are optimum for analysis.

. . . differences in imagery collected at different times of the year is substantial. Furthermore, . . . imagery would have to be collected over a period of several years to . . . sample the possible variations.

Analysis shows that band 7 spring imagery has some advantages over fall imagery in the same band . . . However, fall imagery is useful for adding detail to gross lithologic units.

(Ge) During the late summer passes, it was found that band 5 produced superior results, but as the year progressed, band 7 was found to yield the images with the greatest amount of clarity and detail.

(Ho) These studies show . . . that the best time for mapping vegetation in this area is early fall and late summer . . .

(Is) The comparison was made using all linears seen on the fall and winter imagery, although very few linears were seen on the winter image that did not appear on the fall image.

In the course of this analysis, a comparison was made between the linear information revealed in summer-fall versus winter imagery at 1:2,500,000. Much less detail is present in the summer-fall mosaic than in the winter mosaic. This may be due to the higher contrast of the winter print, and in part to a poor image product for the central New York scene. The longest continuous linear measured on any image of the Allegheny Plateau is on the winter image at 1:2,500,000, and appears to extend continuously for more than 90 kilometers. It can be seen that the winter image emphasizes the shorter linears more effectively than the fall image does, especially in the Catskill Mountains which are located in the northwestern portion of the scene. Many of the tonal signatures on the fall image are topographically expressed on the winter image, probably due to shadow enhancement occasioned by the lower angle of solar illumination in winter.

As expected, snow covered open fields and lakes appear white, but it was surprising to find that the extensive forests of the Adirondacks, the Tug Hill Plateau, the interfluves of the Allegheny Plateau, and

(Is) scattered woodlands elsewhere, are dark grey to black in all spectral bands despite a deep ground cover of dry snow (these were the coldest days of the month, the maximum temperature reached in Albany being 7°F). This unusually low albedo characterizes not only the conifer forests of the high peaks area, where it is to be expected, but also the mixed hardwood forests at lower elevations. It thus appears that, although in winter at conventional flight elevations such hardwood forests would have a high or intermediate albedo, at the lower resolution of satellite imagery the low winter shadows, dominates the spectral response.

In terms of geological usefulness, the major advantage of the winter imagery observed at 1:1,000,000 is the suppression of terrain noise produced by land use patterns in agricultural areas. This results in the increased detectability of small scale topographic features. The most notable examples are individual drumlins, which can be identified directly as topographic features rather than indirectly by their control of agricultural land use patterns.

A comparison of linears on fall and winter imagery covering southeastern New York State showed that the majority of linears are observable on the fall imagery, but some additional short linears ($\geq$4 km) are seen on the winter imagery. Tonal linears are more readily seen on the fall imagery, and many of these are expressed as topographic linears on the winter imagery.

(Kn) Detectability of individual lithologic contacts is highly variable, and is dependent on such factors as sun azimuth and elevation, vegetation, snow cover and soil moisture.

(Kr) As detailed and illustrated in this study of the playa lakes at Qom, Shiraz, and Neriz, the repetitive coverage of Landsat-1 is ideally suited to provide a seasonal record and an annual inventory of the hydrologic balance of water bodies that are otherwise not measured or would be difficult and expensive to measure by other means. Only a modest amount of ground control (water depth measurements at maximum and intermediate stages) would increase the reliability of water balance calculations significantly.

(Li) The repetitive ERTS-1 imagery coverage has provided unique information related to seasonal changes of vegetation patterns and varied illumination of topography. Similar repetitive aircraft imagery has not generally been available.

(Li) For hydrological investigations, ERTS imagery covering a full seasonal span is valuable for understanding annual changes in the expression of vegetation, intermittent streams and spring flow.

Recognition of fault scarps in alluvium is frequently dependent on the sun azimuth and elevation. For this reason, it is valuable to examine ERTS-1 imagery recorded over a full seasonal span.

(Mc) The pattern of vegetation visible on seasonal Landsat images may be a key to identifying those areas that are most capable of being protected from degradation.

(Mr) Repetitive MSS coverage provides a great deal more information than single season or single spectral band coverage:

- Summer imagery - Least informative - vegetation cover conceals most information on soils and surficial deposits. MSS 5 optimum for geology in summer.
- Winter imagery - snow enhancement - maximum data on topography.
- Spring - useful for mapping soil associations that define surficial-geologic features. Best images were taken at the start of the growing season, after croplands have been plowed, while vegetation is still sparse.

Comparative value of the various bands at different seasons. The green band (4) is not very useful at any time of year in the Great Plains-Midwest because its resolution and contrast are severely degraded by light-scattering and poor atmospheric transmissibility of these wavelengths due to the high atmospheric humidity and haze. The importance of the other multispectral bands varies with the season.

In summer, red band (5) images are the most informative. They show best the differences in land use such as between cropland and woodland; however, the ubiquitous vegetative cover obscures any primary information about earth materials. The higher reflectance of plant foliage of all types in summer renders the infrared bands (6 and 7) almost useless except for information about water bodies.

In fall, the red band becomes relatively less informative because with decrease of foliage the infrared bands provide increased information on soils and surficial deposits. Maximum information on soils and surficial deposits is obtained from bare, newly plowed fields, and from

(Mr) images taken soon after widespread rains, because then the differences in soil drainage show most clearly as tonal differences in the IR bands. Well drained soils are light toned and poorly drained soils are dark toned. Commonly the tonal differences are somewhat more distinct on band 7 than on band 6.

In winter, the red and infrared bands generally give less information on earth materials than in fall and spring images. Snow cover, however, greatly enhances the topographic detail visible in the images. Spring images definitely provide the best information on soils and surficial deposits in this region, better even than fall images.

The synoptic multiseasonal views of the entire test region provided by the ERTS images afforded a superb new tool for identifying these linears, showing that they are much more numerous than previously was suspected.

(Ro) . . . the surface expression of regional-to-continental-scale tectonic features can be analyzed during different seasons . . .

Snow enhancements of topography in the winter images . . . was especially valuable. Band 7 winter images provided more additional linear data than did the other bands.

The change in seasons . . . permitted detection of additional linears . . .

(Sa) The . . . best season of coverage depends on the problem to be solved and the region to be studied.

Table 1. Summary of Wavelength and Seasonal Study Results

Region	Features Sought	Best Band	Best Time of Year	Remarks
Montana	Linears Tonals Water	5 or 7 5 7	Fall Fall Fall	
Colorado	Linears Tonals Water	7 5 7	Winter Fall Fall	Band 5 fall coverage also good
New Mexico	Linears Tonals Water	5 5 7	Winter Spring or fall Spring or fall	Band 7 spring coverage also good
Canada (Eastern)	Linears Tonals Water Roads and Trails	5 5 7 5	Spring Summer Summer Summer	Band 7 in the summer also good Band 7 early fall coverage also good Band 5 in winter also good
Alaska (Northern)	Linears Tonals Water Features	7 7 7	Late summer Late summer Late summer	Early winter also good

15. Temporal Changes Observed (Relative to Dynamic Events)

(Ho) The contrast between both stable and active dunes and the surroundings was . . . apparent on Landsat color images.

. . . for modern ice fields, monitoring glaciers, and mapping ablating areas are possible using Landsat imagery.

(Kr) A dramatic increase in the size of a lake was observed in a December image. Since only moderate precipitation had occurred, the investigator thought it reasonable to assume that there had been sufficient ground water recharge during October and November so that the December runoff quickly accumulated at the surface of the playa.

16. Relations to Soil and/or Vegetation Considered

(Co) Bands 5 and 7 are particularly useful for mapping rock units, because vegetation is usually dark in 5 and bright in 7 . . . Native vegetation . . . is sensitive to factors related to the underlying geology and hydrology . . . where vegetation is sparse, units . . . may often be distinguished by the tone differences seen on different bands.

Fresh bedrock and soil exposures generally appear brighter on all bands than do corresponding weathered and plant covered exposures.

The mapping of the Quaternary sand cover is facilitated by the strong contrast between the sand and the surrounding units.

(Kn) Six mappable geologic units were discriminated on the basis of the lack of vegetation and soil cover.

Lithologic contacts can be best discriminated in imagery where vegetation contrast is at a maximum.

Most lithologic contacts are masked by soil, alluvium and vegetation.

Topography and vegetation are the most useful mapping criteria.

Conceptually, vegetation differences should also be sensitive to band, yet the results of the tests suggest that either (1) the vegetation contrasts observed are not sensitive to band or (2) the vegetation contrasts observed are subdued by other factors controlled by image set (i.e., snow cover, sun-angle).

(Ko) It was found that geologic units could be mapped where there was no major change in vegetation or where transitions coincide with formation contacts.

(Mr) In the semi arid region (south of the Platte River) vegetation is less of an impediment to photointerpretative geologic-terrain mapping than in the more humid Midwest.

(Vi) Vigorous vegetation has the lowest dynamic voltage levels in the red/green ratios (except for water) . . . Ratio values between the extremes of dense vegetation and exposed red Chugwater Formation are controlled by: (1) relative reflectance in these two bands; (2) the percentage of vegetation cover; and (3) the vigor of the vegetation.

17. Specific Small Features Looked For (Resolution Test)

(Co) A working limit for recognition of linears by their own reflectivities seems to be 20 meters.

. . . ponds are visible at the limits of resolution, namely as small as 34 meters in radius.

(La) The recognition of a vehicular scar north of Umiat on Landsat images indicates that . . . under certain circumstances they can be mapped using Landsat.

18. Stereo Effects Utilized

(Ge) One disappointing aspect of Landsat imagery has been that the stereo effect obtained by viewing side-lapping pairs in a stereopair is negligible.

(Kn) ". . . Use of stereoscopic analysis greatly increases the amount and accuracy of the extracted information."

"A method of viewing bands 5 and 6 with a stereoscope was employed and it aided the mapping significantly."

"Pseudostereoscopic viewing, using band 6 and one other band for a stereopair, greatly increased the ability to map lithologic contacts."

"The use of the available stereoscopic viewing capability on Landsat-1 imagery cannot be over-emphasized . . . The use of stereo is particularly valuable in the discrimination of relief, relative rock resistance and qualitative dip estimation."

(Ko) It was found that good stereo could be obtained over large areas by using the same scene on different dates.

(Li) The stereoscopic U2 coverage has been extremely useful in detailed structural analysis and has guided selection of key areas to be studied on the ground.

Stereoscopic imagery coverage would facilitate the use of orbital remote sensing in many applications to terrane analysis, especially structural geology, geomorphology, engineering geology, and related disciplines. Stereoscopic coverage might be achieved by increased sidelap of Multispectral Scanner (MSS) imagery or forward overlap of Return Beam Vidicon (RBV) imagery.

(Mr)

1. Stereoscopic coverage is limited to the sides of images that overlap with images from adjacent orbital tracks; commonly 40 to 60 percent of a frame has such sidelap stereoscopic coverage (stereovision is not provided by the 10 percent endlap of consecutive frames along a track because the same scan lines appear in the overlapping areas of both frames);
2. The high orbital altitude produces very little parallax, and hence very little stereorelief; and
3. The low relief of most of the Great Plains-Midwest, combined with the limited parallax, means that the stereovision provided by the images is inadequate to assist in distinguishing most landforms.

19. Aircraft Remote Sensor Data Utilized

(Ho) As a result of the Landsat and Skylab programs plus studies done by the USGS for NASA in Wyoming in recent years, some 65 percent of the state has been covered by up-to-date aerial photography. The primary use of this aircraft support has been in checking interpretations of satellite imagery and in adding essential detail in these studies.

. . . mapping projects in . . . parts of Wyoming have demonstrated that Landsat color composites and low-altitude aircraft photography greatly augment construction of an accurate geologic reconnaissance map.

20. Aerial Photos Used and Compared

(Br) A comparative study of Landsat with 1:40,000 scale aerial photography reveals that Landsat images can produce only 60% of the amount of detail that can be gathered from the photographs. The scale factor is the primary reason for this fact.

(Ge) . . . it was found that the aircraft data were useful in discerning small scale features not visible on the imagery . . .

Even after careful scrutiny, the aircraft data failed to yield conclusive evidence of the fault nature of this lineament.

In summary, it can . . . be stated that the amount of new information gleaned from the aircraft data . . . does not justify the expense involved in its collection.

(Ho) U-2 imagery was used to distinguish many of the large diabase dikes that cut the granitic rocks . . .

(Is) The most economical and effective way to locate the feature on the ground was found to be by observation and photography from low level aircraft.

Field studies carried on both by conventional ground methods and by observation and low level aircraft, has permitted further definition and identification of ERTS-1 linear anomalies. The result has been to declassify some, reclassify others, and to add a small additional number which were originally considered too marginally expressed on the imagery to be designated as photogeologic linears.

More impressive, however, is the fact that the two short N 75 E linears, spaced only 1 km apart, with the shorter one being less than 2 km long, can be discerned on the imagery; we would have been unwilling to identify such short lines on the imagery as linears without the assurance provided by the aerial photography.

Low level aerial reconnaissance of the Stony Clove linear confirms it as a well defined topographic lineament.

In the Adirondacks, the use of low level aerial observation and photography, coupled with ground investigation, has resulted in the elimination of about five percent of the original number of ERTS-1 linear

(Is) features remaining after the exclusion of those which are either man-caused or lithologically controlled. In addition, it has led to the discovery of a system of intersecting orthogonal and oblique fractures which cut the relatively homogeneous and massive Marcy Massif metanorthosite.

(Kn) "Aircraft data was used to document tonal, textural, topographic and vegetation differences. Also, aircraft data were used to determine surface conditions which hindered discrimination, and analyze landforms.

In areas of known mineralization, aircraft data were used to document the surface manifestations of the deposits."

(Li) The X15 photographs provide a synoptic scale intermediate between ERTS-1 MSS imagery and U2 aircraft photography, and they have been used in several areas of interest where U2 photographs were unavailable. X15 photography along the California-Nevada border has complemented U2 and ERTS-1 imagery analysis and supported field reconnaissance of fault patterns in Pahrump Valley.

The U2 photography has been the most generally available and most widely used subsidiary data in the investigation. The primary use of the U2 imagery has been in providing detail for geologic studies of anomalies recognized in the ERTS-1 imagery. The stereoscopic U2 coverage has been extremely useful in detailed structural analysis and has guided selection of key areas to be studied on the ground. The color infrared U2 photography has provided excellent detail of vegetation, soil, and rock-type variation and has been used in the detailed mapping of faults in alluvium in the Lake Mead area and in interpretation of fault patterns in volcanic rocks in Fish Lake Valley, Nevada.

To complement field reconnaissance in critical areas, low altitude fixed-wing reconnaissance has been flown by Argus Exploration Company personnel. During these flights, color and color infrared 35 mm photographs have been taken at various times of day to provide detailed views of inaccessible areas. Fixed-wing reconnaissance has played an important part in studying the style, continuity and patterns of deformation in a large area south of Lake Mead, Nevada and the late Tertiary and Quaternary fault pattern in Esmeralda County, Nevada. Fixed-wing aerial reconnaissance has proven to be an economical method for preliminary evaluation of geologic and structural anomalies interpreted in ERTS-1 MSS imagery. The information obtained from airborne reconnaissance can be an effective tool for planning and guiding detailed field investigations.

(Mr) Comparison of ERTS interpreted maps, with soil association maps of Illinois shows that the boundaries between certain soil associations are registered much more clearly on the spring infrared ERTS images than on conventional aerial photographs, permitting rapid soil mapping over large regions with a high degree of accuracy.

21. Skylab Data Used and Compared

(Br) Skylab and Landsat are being used to plan the route for a pipeline.

(Ho) Comparisons of Landsat image interpretations and interpretations of Skylab photographic data show that the additional resolution by the Skylab data is valuable in many resource studies.

Rose diagrams . . . show that there are not only more lineations recognized on the Skylab photograph but that the major set strikes north-northwest rather than northeast as is the case for Landsat.

(Mc) Skylab data confirm the presence of the red colors of the inland portions of the Namib Desert. These colors also appear (as a yellow color) on Landsat.

22. Radar Data Used and Compared

(Ho) Nearly all the linear elements previously discerned in SLAR imagery . . . were distinguished on the Landsat imagery.

(Li) The primary value of SLAR is the ability to image topographic and textural patterns using radar illumination of various look directions. Such radar images are completely independent of solar illumination. Like U2 photography (Section 2.5.7) SLAR has proven of value in structural interpretation at a scale intermediate between ERTS-1 and ground based reconnaissance. Enhancement of subtle structure is frequently superior to that achieved in U2 imagery, and SLAR is not degraded by the presence of haze, fog or clouds. The SLAR imagery has provided detailed structural information in areas that are otherwise obscured by shadowing of solar illumination.

23. Relative Percent of Same Features Noted in Landsat, EREP, A/C

(Ho) A comparison of known faults using Skylab and Landsat reveals:

	Skylab (190A)	Landsat
Total number of linears	202	104
Total length of linears	600 km	520 km
Total number of linears that correspond to mapped fault and shear zones	17	13
Total length of corresponding linears	95 km	95 km

(Sa) . . . Some 30 percent of the aerial photo lineaments were not detected on Landsat imagery. The comparison of the two types of data clearly indicates that Landsat lineament data compares favorably with that obtained from more costly conventional photos.

24. Field Checks Carried Out and Role of Field Work Considered

(AG) A total of 11 sites were visited, . . . and in all areas we were able to identify the structural and lithologic features observed in the imagery.

(Ho) Initial field examinations were somewhat disappointing. Units readily recognized in the field could not be distinguished on the imagery.

(Is) Seventeen linears were declassified as unverifiable on the ground as linear features.

About 75 percent of the dark vegetation strips were found to coincide with "straight stream valleys" and were hence transferred from a botanical to a geomorphic category. About 95 percent of the "straight segments of stream courses" were reclassified into other categories, mainly "straight stream valleys."

Ground study of ERTS-1 anomalies in the Adirondacks indicates that: (1) outcrops are even more rare than expected along the traces of topographic lineaments, indicating that for the detection and evaluation of some fracture systems, the representation on ERTS imagery may be the best data obtainable, short of trenching or other excavation; (2) fault breccias are found along some of the north-northeast and northwest trending lineaments; (3) chloritization and slickensiding, without brecciation, were found along one east-west lineament; and (4) closely-spaced joints and a zone of plastic shear was found along another east-west lineament.

(Kr) The reliability of the interpretation is significantly improved if the interpreter is familiar with ground conditions in the image area.

(Li) Ground based reconnaissance of anomalies recognized in ERTS-1 imagery has resulted in identification of previously unreported strike-slip and normal fault systems, structural ground water traps, dike swarms, domal plutonic structures, volcanic centers, and areas of hydrothermal alteration.

An extensive program of ground based field reconnaissance, geologic mapping and literature research was undertaken in order to evaluate the origins and significance of key geologic and structural anomalies interpreted in the ERTS-1 MSS imagery. These investigations were conducted in the diverse geologic, topographic and climatic terranes

of the test site, and have formed the basis for evaluating data analysis and interpretation techniques and potential applications of ERTS-1 data.

A program of literature research and field reconnaissance of key ore deposits has been conducted to determine the causes and significance of their expression in the ERTS-1 imagery. Emphasis is placed on mineralized areas for which ground based data is available, either through our own field work or through published maps and reports. The expression of known mineralized areas has been studied with the objective of recognizing criteria that can be applied to regions where less is known of the economic geology.

(Mc) The acquisition of ground truth from field studies, especially data on the internal structure of stratification, represents the final and critical stage of sand-sea investigation. This is best done by a direct approach consisting of wetting the sand, cutting trenches to expose stratification in three dimensions, and recording the patterns on rubber peels, scale drawings, or photographs.

Apparently, from ground level, the local workers are unable to recognize the regional patterns of dune complexes that are so noticeable on Landsat imagery.

(Mo) Detailed ground surveys are necessary to define the nature of the Yemen belt system.

A 20 km diameter circular feature, evident on the Landsat imagery, has been shown by ground survey to be a breccia-filled cauldron intruded by ring dikes.

(Mr) Considerable "ground truth" is essential for producing a reliable map. The investigators use published geologic and soil maps, topographic maps, unpublished geologic maps and file data, subsurface data and field studies.

(Ro) Geological, geophysical and geochemical field studies of major lineaments and circular features are imperative for determining the origin of these landforms.

(Sa) . . . Landsat lineaments cannot be readily ground checked, unlike single fault or fracture features.

(Sc) An evaluation of the color composites, photogeologic maps and previously acquired field reconnaissance data resulted in the identification of seven (7) sites as new field check targets.

25. Geophysical Data Correlated with Landsat Data

(AG) There appears to be no strict correlation between observed evidence of recent surface breakage and the distribution of earthquake clusters.

(Br) The primary seismic epicenters on the Landsat images are used for correlation to lineaments.

(Ge) It is immediately apparent, when comparing Landsat imagery with epicenter maps of earthquakes which have occurred within recent years, that most larger earthquakes within the state of Alaska occur on or near lineaments which are visible on the imagery.

(Is) A recently published gravity map of the Adirondacks (Simmons and others, 1973) shows a two milligal simple Bouguer negative gravity anomaly over the Cranberry Lake basin. Taken together, the above observations suggest the possibility that the Cranberry Lake anomaly may be a cryptoexplosion structure.

(La) The longer elliptical linears seem to define an area bounded by local magnetic highs . . .

Deflections in contours of an observed gravity map also trend parallel to the straight linears.

The parallelism of deflections in trends of known folds, of alinement of magnetic anomalies, of deflections in gravity contours, and of the trend of the linears, coupled with seismic data suggesting dip reversals in shallow strata, and the coincidence between areas of linears and of distinctive aeromagnetic anomalies, all suggest that the linears represent concealed geologic structures.

The apparent relationship of both straight and curved linears to gravity and magnetic features, and of the total area of linears to an area of distinctive aeromagnetic anomalies, suggests that these geologic structures reflect the character of the basement.

A compilation of a contour map of the total magnetic intensity with the Landsat linears at the same scale reveals a correlation of regional linears to the trends of the magnetic anomalies.

Many of the linears although expressed in undeformed surficial materials, can be related to buried structures by inference from geologic and geophysical data . . .

(Li) The distribution of recorded earthquake epicenters and focal depths in the Argus Exploration Company test site have been compiled in order to investigate the interrelationships between seismicity and regional Cenozoic structural patterns visible in the ERTS-1 MSS imagery. To gain a perspective of this relationship we have studied correlations between the distributions of recorded earthquake epicenters, known systems of active faulting and the Cenozoic structural patterns visible in the ERTS-1 MSS imagery.

(Ro) Several lines of geophysical evidence have been examined and synthesized to evaluate the origin of a newly identified circular feature. Regional aeromagnetic data compiled for the conterminous U.S. show a distinctive total-intensity low within the circular feature . . . Analysis of seismic refraction profiles also shows the anomalous character of the crust in the vicinity . . .

A distinct zone of aligned magnetic anomalies coincides with the Oregon-Nevada lineament System for about 200 km.

26. Rock Types Discriminated and/or Identified

(Br) Ignimbrites were recognized on the basis of their color signature.

(Co) Generally, it is not possible to separate one Permian unit from another, . . .

Quaternary sand cover in the Texas Panhandle is easily mapped from Landsat imagery. Moreover, the Landsat mapping coincides precisely with published state maps.

(Ho) Mapping of volcanic terrane . . . produced mixed results.

Red-bed facies of the continental Tertiary . . . can be identified on Landsat images.

The geologic map shows 9 lithologic subdivisions whereas the Landsat geologic map shows 25 units: For example, one unit, the Masaverde Formation, can be subdivided into three units - a sandstone, shale, and a Teapot sandstone unit.

Differentiation of volcanic, sedimentary, igneous and metamorphic lithologies was best accomplished using a standard color composite image.

(Kn) "Mapping the location and distribution of rocks and soils . . . is largely controlled by the ability of the photo interpreter to discriminate between lithologic units on the imagery. Usually lithologic units cannot be identified as to composition."

"The ability to discriminate between two rock types on snow covered Landsat scenes depends largely on the weathering characteristics and relative resistance to erosion of the rock types present."

"The discrimination of mappable rock units was based largely on topographic expression related to resistant or non-resistant units and overall mountainous terrain vs. low-lying terrain.

(Ko) The youngest lava flows in New Mexico are clearly evident on the Landsat images.

The Permian Abo Formation (red shales and calcareous siltstones) can be readily identified on the color composite by its yellow-brown signature.

(Mo) Intrusions of a granite–syenite mass with minor associated volcanic material are evident in the imagery.

A field of phonolite–trachyte plugs shows up clearly.

Young basalt flows appear darker than the surrounding older units.

The superposition of Cretaceous sandstone on gypsum on limestone on Jurassic gypsum can be identified and mapped in detail.

Lithological types are rarely distinguishable in the Precambrian.

(Ro) Subtle spectral reflectance differences among many rock types have been enhanced by ratioing and stretching.

27. Rock Unit Contacts Selected

(Br) Because of the large area view of Landsat it is possible to outline the regional boundaries of the volcanic formations.

(Co) In general, we found it difficult to recognize many mapped lithologic boundaries. The difficulty arises partly because of the effects of agriculture and the fact that in Landsat images most rock units in the area have no readily distinguishable tonal differences from adjacent mapped units.

Many factors aid in distinguishing known units. These same factors can be used to define new "imaged units" or "photolithologic units." Units are easily established when there are contrasts in any or all of the following features: grain size, degree consolidation, plant growth, agricultural practices, surface effects of ground water, topographic expression (e.g., plateaus, badlands, rolling hills, cliffs, stream density and/or pattern), tone or reflectivity.

One example of successful lithologic mapping is the Wellington-Garber contact where a moderate topographic and vegetation contrast occurs. In fact, we were able to redefine the contact and revise existing maps changing the position of the contact 10 to 12 kilometers in some places.

(Ho) Major lithologic units, such as volcanic, sedimentary, and crystalline rocks . . . are distinguishable but most of the pyroclastics have similar reflectance characteristics.

Over thirty rock units ranging in age from Precambrian to recent were mapped . . .

(Kn) How well a contact between two rock types is expressed on the Landsat imagery studied depends upon the attitude of the contact (horizontal, inclined, vertical) and the composition and relative resistance to erosion of the adjacent rock types. Contacts between flat-lying sedimentary rocks or volcanic rocks on the steep slopes of mountains and on the sides of deep narrow canyons are generally poorly expressed. Among the most easily detected contacts in the scenes studied are:

1. bedrock vs. alluvium - San Luis Valley and Arkansas Valley (central Colorado scene)
2. sedimentary rocks vs. crystalline rocks - vicinity of Pikes Peak and Canon City

(Kn) 3. contacts between different sedimentary rocks in folded (Canon City) or tilted sequences (south edge of San Juan Mountains).

In most cases, detection and mapping of contacts is restricted to contacts between major lithologic groups or sometimes between units within thick sequences of sedimentary rocks.

<u>Comparison of Overall Band Detectability</u> — The initial step in data analysis was to test the mean detectability (of lithologic contacts) between the four bands of Landsat MSS imagery. Table 7 summarizes the partially reduced detectability data used in the tests.

Band	Percent Detectability Scores	Number Observations	Average Detectability	Sum Squares
4	18.7	91	0.2054	8.01
5	24.9	91	0.2736	11.83
6	18.9	91	0.2076	7.73
7	16.7	91	0.1780	6.91

Inspection of the average detectability in each of the four bands (Table 7) suggests that the detectability in band 5 may be significantly better than in the remaining three bands.

Summation of results - Rock Unit Boundary detection:

1. Lithologic contacts are generally most easily seen on Landsat MSS band 5 imagery.
2. In general, the time of year the imagery was acquired (image set) is not a significant factor.
3. The detectability of individual lithologic contacts on Landsat MSS imagery is highly variable.
4. The band of imagery studied is <u>not</u> important in the detection of individual contacts.
5. There is no "best" band of imagery to be used with a given image set.

(Kn) Seemingly, the "best" Landsat-1 imagery for detecting lithologic contacts would be that imagery in which:

1. Topographic expression is fully enhanced.
2. Vegetation contrast is at a maximum, either due to growth cycle differences or seasonal, daily or hourly enhancement factors.
3. Spectral contrast is at a maximum.

(Ko) Consistent high relief hampered formation recognition capabilities . . . no differentiation can be made between an extrusive and adjacent sediments.

Where relief and elevation are not too high, formation contacts can be easily identified.

(Mo) . . . lithological boundaries can be very sharply etched on the imagery, especially in river valleys or along major fault escarpments.

(Ro) A limited number of geologic contacts can be detected within the ranges. However, many geologic contacts which otherwise might be seen are obscured by topography and by vegetation.

(Vi) An analog image of a ratio 5/4 resulted in the recognition of the Triassic redbeds. The ability to recognize these units in this ratio is based on hematites increasing reflectance with increasing wavelength in the 0.5 - 0.7μm range.

Areas where the exposed rock is red, orange or orange-yellow, indicating high reflectivities in the 0.6 to 0.7μm region, should yield abnormally high values of the ratio . . .

28. Comparisons Made with Published Geologic Maps

(AG) . . . we recognized in Landsat imagery many possible faults belonging to all three major systems which do not appear in the geological maps . . .

(Br) The presence of sedimentary rocks was determined in areas which had previously been considered to be crystalline.

(Co) Although relief is low and dips are gentle, we are able to map some lithologic units that correspond to published map units. The correspondence of Landsat-derived units to published units is generally inexact . . .

Correspondence between published and Landsat-based maps is good.

However, on the basis of Landsat data we can not confidently assign given mapped areas to the same units as those appearing in the literature.

(Ho) Thirty-four of the forty-nine known intrusive centers were identified using Landsat imagery.

Soil maps compiled from Landsat image interpretations closely match regional maps prepared using genetic soil classifications, but these maps do not fit current soil classification schemes.

A geologic map of the Arminto area of central Wyoming was prepared from interpretation of a Landsat color composite . . . When compared with the state geologic map, it was found that units mapped from tonal variations are surprisingly close to those chosen as formations by field geologists—particularly since most of these major units are rock-vegetation units.

(Is) The linear features seen on the imagery include the majority of known faults and topographic lineaments shown on the geologic map of New York at 1:250,000.

(Ko) On the 1965 state geologic map a very small portion of the San Marcial flow is mapped as being covered by dune sand, yet the Landsat color composite shows a much larger area to be inundated.

(La) Enlargements of Landsat images to a scale of 1:250,000 has permitted extrapolations of data into unmapped areas, and has resulted in the recognition of structural and stratigraphic anomalies that suggest new interpretations of the geology.

(Mo) The accuracy of the geological mapping of Didson and Matheson . . . for the Kenya-Ethiopia border region and southward is strikingly confirmed by Landsat imagery.

(Mr) The selection of test sites included a mixture of well mapped and poorly mapped areas, so that the well mapped areas could provide checks on the accuracy of the maps compiled from Landsat imagery.

29. Relative Mapping Accuracies in Humid, Semiarid, Arid Settings

No entries

30. Geomorphic Units Recognized and Characterized

(Br) Moraine deposits have been identified because of their elongated shape and sharp profiles. Salt pans, saline deposits, and fluvio-lacustral plains have also been identified.

Calderas and craters are evident on many of the Landsat images.

Relative ages of the volcanoes can be estimated based on the relative erosion of the volcanoes.

(Ho) . . . mapping of glacial features and sedimentary deposits of glacial origin, mapping of geomorphic landforms and Quaternary deposits . . . has been possible . . .

The mapping of large-scale landforms such as pediments is possible because the deposits on pediment surfaces are often characterized by vegetation.

Landsat images were utilized to establish a geomorphic province classification for Wyoming . . . The Province was divided into ten basins and associated uplifted regions . . . A description of each area includes geography, size, boundaries, drainage, topography . . .

(Kn) The areal analysis of landforms was found to be useful for understanding the geologic history of the underlying crust. Landform analysis in this investigation was aimed primarily at the interpretation of the location and distribution of rocks and geologic structures.

Landforms are most easily seen on low sun angle, wintertime Landsat imagery of Colorado, terraces and pediments associated with streams can be best discriminated on high sun-angle imagery.

(Kr) A thick salt crust was observed which covers two-thirds of the playa and gradually thins towards this wet area. The salt crust is sharply delineated by polygons ranging from one to 6 m in diameter with ridges generally 6 to 20 cm high, respectively. A section of salt crust 6.8 m thick immediately north of Sargardani Island, adjacent to the south coast, shows no significant disconformities. The surficial layering sequence is thought to suggest that the depositional environment of this playa has alternated from conditions of high evaporation and low runoff (salt crust formation) such as currently prevail, to conditions of lower evaporation and higher runoff forming water surpluses that resulted in lakes and consequently in lacustrine sediments.

(Kr) The combination of MSS band ratios 4/6 blue, 5/7 red, 5/6 yellow and 4/7 green was found to provide excellent contrast between the two main playa areas and between the zones within these areas. Brown central and peripheral zones of the wet area are smooth white salt recently precipitated or washed. Yellow zones are wet and greenish-yellow locations may be films of water, especially in the south-central part of the wet area. The light blue annular zone around the playa is most likely ponded water. The blue to brown area is salt crust with raised-ridge polygons . . .

(Li) The western boundary of the Colorado Plateau is marked in the ERTS-1 imagery by two prominent west-facing escarpments . . .

(Mc) An objective classification of sand-sea landforms has been completed. Topographic patterns of sand-seas have been identified according to their regional morophology. Five genetic dune types have been classified: (1) parallel straight; (2) parallel wavy; (3) radial; (4) parabolic; and (5) sheets.

(Mr) The authors recognized in winter imagery (without the aid of ground truth) three terrain types: dune fields, valley bottom-lands (flood plains and terraces along rivers) and bedrock escarpments and surfaces of several types.

Spring imagery of Illinois displays two chief geologic terrain units - Wisconsin till plain - moist (dark tones) soil, and the Illinoian till plain - dry (light tones) soil. Also, hills of well drained sand and gravel (Kames).

A major buried valley is identified by analysis of variations in the width of the Illinois River. Coal strip mine area indicated bedrock close to the surface.

The configuration and patterns of dunes and interdune depressions can be distinguished clearly, especially in snow covered imagery.

An excellent correlation was found between known areas of late Quarternary alluvium and the "valley lowlands" shown on the phase 1 maps. Good correlations also were noted between known and ERTS interpreted dune fields and uplands having thick deposits of Quaternary loess and alluvium.

(Sc) By examination of digitally enhanced false color composites it can be seen that much of the dune sand is being transported southeastward.

31. Comparisons to Known Linear Features Made

(AG) Landsat imagery shows the Walker Lane zone as a definite major fault zone characterized by well-recognized fault traces.

(Co) An early surprise in viewing Landsat was the discovery of linears of great length that seemed not to have been recorded in the literature. Most of these are subtle alignments not defined by any single major feature.

A comparison was made of the interpreted linears with published linears . . . Although we can confirm or extend many published faults there are two published sets for which we see little or no evidence. These are the N 60 W set in Oklahoma and N 40 W set in Texas.

(Kn) Although many lineaments can be related to known faults, shear zones, major joint trends and lithologic contacts, there are commonly many more lineaments on an Landsat scene than can be definitely related to a known structural featur

(Ko) One lineament found appea... to bisect the entire state. The northern part of the lineament is the Nacimiento fault; northern part links up with lithologic boundaries; farther south it coincides with the Joyita Hills frontal fault.

(Mr) Conventional topographic maps tend to emphasize the stream courses and to obscure much of the valley linearity. Special shaded-relief maps, show some of the more important linears, but generally not with the completeness and detail of the ERTS images.

(Ro) The linear features, or linears, vary from approximately two (2) to several hundred km. Although some are curved, most are essentially linear. Circular features range from 8 to 150km in diameter.

Twenty-three percent of the linears can be correlated with mapped faults; furthermore, only 15 percent of all mapped faults were mapped as linears.

Linears related to faulting constitute 22 percent of the total linears . . . Only 19 percent of the faults were detected by the linears.

(Ro) The percentage of faults detected by the linears averages 24 percent . . . The degree of correlation is affected by the length of the faults in each area and . . . by the dominant type of faulting in each area . . . The type of faulting present also affects the number of faults detected by linears. Thrust faults are much less detectable than are normal and transcurrent faults.

A derivative overlay was prepared showing the correspondence of mapped faults with the major lineaments . . . Analysis reveals a 79 percent agreement between the major lineaments and mapped faults.

Although a total of 172 faults longer than 10 km relate to the major lineaments, 415 faults longer than 10 km were not detected.

Major lineaments have substantially higher correlation with mapped faults than do all linear features . . . However, major lineament analysis from Landsat imagery is not a substitute for mapping in the field.

(Sa) The Texas "lineament," long inferred to be a major weakness zone, appears as a very diffuse zone of 12 major lineaments and many linears . . .

32. Types, Sizes, Distributions and Orientations of Linears Noted

(Br) Three principal fault trends have been identified: (1) N45 - 55E; (2) N70W; E - W; and (3) N10 - 20W.

The faults that affect the volcanic formations are much more visible on the Landsat images than on the ground.

(Co) Differences in the distribution and length of linears appearing on the same imagery at two different scales were noted . . . Interpretations at 1:250,000 consistently produced linears of greater length than did those at 1:1,000,000.

. . . fault and joint traces are most frequently revealed by drainage alinements.

Many newly identified linears range from 20 to 150 km or more long and may be indicated by a subtle alinement of many kinds of features . . . such as vegetation lines, straight streams, abrupt changes in streams, tonal differences in soils, . . .

Most linears . . . were recognized most easily on bands 5 and 7, although large numbers can be recognized on 4 and 6 with more careful study. . . . also, although bands 5 and 7 are both excellent for tracing linears, they exhibit different fractures and must be used to complement each other . . . There are linears seen on band 4 that cannot be seen on other bands.

There is evidence that at least the regional sets of linears are fault related . . . Some of these linears coincide with oil producing structures . . .

(Ho) Another study by Blackstone and others of 616 linear elements of the Laramie Mountains of Southeast Wyoming does show a relationship between linear elements of the uplift and folds in the basement. Northeast-trending linear elements in the Laramie range correspond well with the dominant orientation of numerous Laramide folds in areas marginal to the uplift.

(Is) We employ three classes of terminology for linears: (1) a non-genetic term to describe the feature as seen on an aerial photograph or satellite image; (2) another non-genetic term to describe the feature on the ground; and (3) a term to classify the feature genetically. In the first category are terms such as "circular feature," "linear feature" (or simply "linear," a short form of "photolinear"), but <u>not</u> lineament. We use "linear" to signify a line on an aerial photograph of image, irrespective of its validity on the ground (e.g., whether it turns out to

(Is) be a cultural feature, a geological feature, an artifact, or an unexplained line). Linears can be designated as "topographic" or "tonal," depending upon their appearance in the photography or imagery.

We reserve the term "lineament," on the other hand, for a naturally occurring feature, i.e., one which has been confirmed to exist on the ground.

The combined lengths of linears observed in ERTS-1 imagery of New York State exceeds 26,580 km.

The most spectacular area of linear display in the state . . . is the Adirondack Mountain Region.

Surprisingly, all the linears detected at 1:250,000 were also observable at 1:500,000. The majority of the linears seen at the above scales had also been seen at 1:1,000,000 except for 433 new short linears, the majority of which are less than 5 km long, but have a combined length of 2155 km. When this latter group were searched for on the 1:1,000,000 imagery, 87 percent were not observed, 10 percent were observed without reservation, and 3 percent were seen with slight difficulty.

The multiscale comparison of ERTS images showed that the shortest lines generally classified as linears at the various scales were: 1:2,500,000, 5 km; 1:1,000,000, 2 km; 1:500,000, 1 km; 1:250,000, 1/2 km. This expectable inverse linear relationship between scale of imagery and length of linears suggests that a line must be at least 1.5 - 2 mm long, on any scale image, before an interpreter confidently identifies it as a "straight line." It was also observed that numerous short, aligned segments at the larger scales appear to coalesce into single long linears at the smaller scales.

All ERTS-1 linears confirmed to date have been topographic features on the ground, although many of these appear on the imagery as tonal linears without relief, or as combinations of tonal and topographic features. In general, the linears extending across physiographic, geologic and tectonic provinces are quite distinctive (i.e., topographic vs. tonal expression, length, straightness or concavity, density, spacing and cross-cutting relationships).

(Kn) "The most apparent structural features are lineaments defined by topography, drainage patterns and linear tonal changes . . ." Although many lineaments can be related to known faults, shear zones, major joint trends and lithologic contacts, there are commonly many more lineaments on a Landsat scene than can be definitely related to a known structural feature. Fractures (faults, shear zones and major joint trends) are generally well-expressed in crystalline rocks as straight

(Kn) topographic lows formed by preferential or more rapid weathering along the fracture. Faults in gently dipping sedimentary rocks are most easily seen on low sun-angle, snow covered Landsat scenes. These faults generally appear as tonal alignments; the same faults are much less obvious on the snow free scenes.

Major faults and fault zones often appear as linear breaks in topography.

Two images were selected for their excellent expression of linear features. Their main attributes are low sun elevation and near maximum snow cover. Since a significant proportion of linears is the result of shadow enhancement of topographic features, the lowest sun elevation was selected; it was the minimum available nearest the winter solstice, approximately 23 degrees. This sun elevation is not the optimum for maximum shadow enhancement of the topography in central Colorado, because slopes less than this are not shadow enhanced. In addition to this restriction, there is selective shadow enhancement of linears as a function of deviation from the sun azimuth, which was approximately S.30W.

"The detectability of linears and linear trends . . . varies greatly between image generations and depends on sun attitude and surficial tonal contrasts due to seasonal effects.

"The high resolution of Landsat imagery allows detection and correction of longer linear features than is possible with relief and topographic maps."

(Ko) Bands 6 and 7 were satisfactory for lineament analysis.

The investigator has identified many circular features, and only some can be accounted for by existing data. Some of the features which may produce circular expressions on Landsat are:

<u>Geomorphic</u>

1. Karst-type solution
2. Circular alluvial fan development
3. Radial and annular drainage expressions
4. Erosional remnants
5. Topographic basins

<u>Tectonic</u>

1. Plunging anticlines and synclines
2. Volcanic-tectonic depressions and cauldrons
3. Volcanic cones
4. Exposed intrusives
5. Salt domes

<u>Man-made</u>

1. Circular irrigation fields
2. Miscellaneous, i.e., warhead test area

(Ko) Lineament patterns have been found to be the following: some are faults; others indicate fold trends or dikes; and others are unidentified. Some unidentified lineaments appear to parallel or branch off from major structural zones. Some of the lineaments correspond to facies changes.

(La) . . . short linears commonly reflect a single geomorphic vegetational or soil characteristic and on field examination, may be ascribed to a single geologic cause.

Previously unrecognized linears in the Arctic coastal plain are expressed as: (1) straight nearly east trending alinements of small lakes, of distortions in the shorelines of larger lakes, and of linear areas between groups of lakes; . . . (2) curvilinear alinements, . . .

The trace of regional linears (over 160 km long) is defined by a mixture of criteria, such as topographic alinements, drainage courses, and lines of tonal change and vegetal changes.

Space image linears in Alaska vary in length from 10 km to over 100 km. In general, they may be grouped into three size ranges - 10 to about 200 km, about 200 to 1000 km, and >1000 km (roughly 10 to 100 miles, 100 to 600 miles, and >600 miles). The frequency of linears varies. The linears also vary widely in trend and include giant curved linears. Well defined sets of linears are apparent in the giant linear group and in the short oriented lake linears, but only one orthogonal set is common to both. Linears of less than 1000 km length in the Yukon-Tanana Upland display a greater variation in compass trends, those shorter than 200 km exhibiting the largest variation.

It is suggested that the shortest and most sharply defined linears . . . may not represent fundamental regional tectonic patterns . . . The longer linears stem from older, more fundamental geologic features.

(Mo) A previously unreported system of narrow, gently curvilinear belts trending for at least 300 km has been identified.

Major lineaments can be identified on the Landsat imagery as expressed through a thick lava cover.

Some of the lineaments seen on Landsat may be dikes or dike swarms.

(Mr) The stream valleys (or segments of valleys) tend to be alined in one of four principal "preferred" orientations: northeast, northwest, slightly east of north, and east-west. These orientations parallel many known faults and folds in the area; hence, it is possible that the alinements of many stream valleys may have been controlled by geologic structures such as faults and master joints.

Geologic linears (fault or joint related) are displayed in ERTS images of the Great Plains-Midwest principally by straight or slightly curved valleys, but in some cases, for the relatively rare faults with considerable throw, by scarps and/or by tonal differences either on opposite sides of the fault or as a band along the fault zone.

The ERTS images of the Great Plains-Midwest (particularly spring IR ones) emphasize the stream valleys, especially their bottomlands - and thus graphically portray the linear valley segments that best reveal the geologic linears. Thus, the geologic linears form an overall rectilinear-parallelogram pattern throughout the region. The linears are most numerous in areas with little or no surficial mantle over bedrock, thus they are most common south of the glacial limit; they are common in parts of the pre-Wisconsinan drift plains, and rare to absent on the Wisconsinan till plains.

(Ro) Most linears are particularly concentrated in the mountain ranges where topographic, textural and tonal enhancement is highest, sparsely scattered linears occur within the alluvial basins.

Both bands 5 and 7 are necessary for detection of linears because some linears and patterns are preferentially enhanced in one or the other of these two bands.

The type of faulting present also affects the number of faults detected. Thrust faults in particular are much less easily detectable . . .

Several categories appear to encompass all of the lineaments origins: (1) boundary between outcrop and alluvium; (2) mountain ridge or series of small ridges; (3) mountain canyons; (4) stream segments; and (5) tonal boundaries . . . of the major lineaments, 65 percent have a single origin.

33. Relative Linears Count Between Summer and Winter Images

No entries

34. Linears Related to Tectonics

(AG) A modification of a model developed by King (1959) has been prepared based on additional data provided by Landsat images. This new model provides an explanation for the transverse linears observed.

The . . . reconstruction of theoretical tectonic movements has revealed a continuous zone of transverse faulting extending from the Colorado River desert to the Pacific.

Landsat imagery is providing evidence that the San Andreas "fault" has not always been one fault.

It became clear from our analysis of Landsat imagery that the shear zones in the Basin and Range Province . . . are arranged in echelon.

Correlation of geological maps with a fault map made it abundantly clear that the shearing deformation has taken place contemporaneously with folding . . . and represents therefore an important tectonic element of the Laramide orogeny.

(Ge) A model is proposed whereby the central part of Alaska is thought to be composed of (relatively) rigid blocks grinding together . . .

(Is) Many of the linear patterns expressed in the ERTS-1 imagery of the Catskills look surprisingly similar to joint maps of outcrops illustrated by Parker. However, the five-or-more joint set model of Nickelsen and Hough would also produce a pattern very similar to the regional linear features observed in the imagery. It seems possible that this conflict of opinions about the nature of jointing may be resolvable by field checking of the linears shown on ERTS-1 imagery. For example, if the joints <u>do</u> gradually rotate across the Plateau, and, if the joint directions <u>are</u> expressed by linears as is the case in the Catskill Mountain part of the Plateau, a gradual rotation should be demonstratable on an ERTS-1 linear map made at a suitable scale.

(La) The Landsat mosaic shows large linears in Alaska which, when plotted, reveals three nearly orthogonal sets.

The occurrence of giant linears of similar nature and trend throughout the North American Cordillera suggest that they reflect fundamental crustal structures that are not peculiar to Alaska.

(Li) Although the pre-Cenozoic structure is locally expressed, the younger deformation has produced the dominant regional structural patterns apparent in the ERTS imagery.

Analysis of ERTS-1 imagery . . . has led to the conception of a tectonic model which relates strike-slip faulting and Cenozoic igneous activity to crustal extension in part of the southern Basin and Range Province.

Guided by the analyses of ERTS-1 imagery, a structural model has been proposed which relates right lateral strike-slip displacement on the Las Vegas shear zone to volcanism, plutonism and inferred crustal extension . . .

(Mo) On the scale of plate tectonics, Landsat imagery has revealed new constraining features and additional transcrustal features.

(Ro) In Nevada, seven major lineament systems have been identified which we believe are deep-seated, pervasive zones of crustal weakness.

Seven major lineament systems warrant further examination with respect to the regional structural implications . . . Three of these systems have already been documented as major crustal features.

35. Alteration Zones Detected

(Ro) Hydrothermally altered areas have been detected using digital computer processing and color compositing.

Despite some erroneous identification of altered areas, an estimated 80 - 90 percent of the green areas in the color ratio composite are related to hydrothermal activity.

36. Exploration Model(s) Developed

(Kn) The results of this experiment suggest that photolineaments on Landsat imagery are fractures or fracture-controlled features and that their distribution may be a guide to metallic mineral deposits in Colorado, and probably other areas as well. Analysis of photo-lineament information contained on Landsat imagery can be a very valuable and inexpensive first step in any mineral exploration program, especially if it is used in conjunction with other sources of geologic information. Imagery acquired from space will probably prove most useful in areas of the world in which less is known about the geology. Moreover, the favorable results of this study suggest that those target areas that do not correspond with known areas of mineralization may, in fact, be new targets for mineral exploration in Colorado.

(La) A significant result has been in the recognition of regional geologic features that may guide in the location of new oil and gas accumulations.

A new metallogenetic hypothesis has been developed, based on the Landsat linears. The new hypothesis postulates that favorable areas form belts parallel to major NW and NE trending fractures, and deposits will be more abundant where such fractures cross.

(Li) A variety of structural features or structures are spatially associated with known mineral deposits in the Argus Exploration Company test site. These include the following:

1. Faults
   - Strike-slip faults
   - Thrust faults
   - Normal faults
   - Structural intersections
2. Features associated with volcanic centers and shallow intrusive bodies, such as radial or concentric dikes and faults, shallow intrusive domes and collapse features.
3. Folds

(Mr) Several models were adopted in this project:

- Small scale geomorphic mapping/surficial materials mapping from Landsat discernible characteristics.
- Interpretation of these characteristics to detect specific geologic-geomorphic features (e.g., moraines, relect moraines, abandoned river valleys, terraces, linears).

(Ro) It is noteworthy that the largest areal density of known ore deposits along the Midas Trench lineament system coincides with the intersection with the Rye Patch system.

. . . the conjugate shear system and the east-trending lineament systems appear to have played an important role in the localization of ore deposits . . .